Fast Optical Comet Search Experiment

H. S. Park, R. M. Bionta
Lawrence Livermore National Laboratory

C. Akerlof
The University of Michigan

E. L. Bowell, E. M. Shoemaker
Lowell Observatory

D. H. Ferguson
EarthWatch Inc.

Long period comets, particularly at solar elongations less than 90 degrees, can cross the orbit of the Earth and therefore are potentially hazardous to the Earth. However, the number and sizes of these objects are not known. No automated effort has ever been made to carry out a systematic search for these comets. A team at Lawrence Livermore National Laboratory is constructing an array of small wide-field-of-view telescopes in an attempt to search for these faint comets within a year. The system consists of an array of 10 cm aperture refractive lenses each viewed by a 2048 x 2048 CCD camera. Each camera has a 5.3 x 5.3° field of view. A system of 4 such cameras can survey the entire night sky in one night. Based on the performance of a single camera prototype, we expect the system to be sensitive down to Mv ~ 17, which is a full 6 magnitudes deeper sensitivity than achieved by dedicated amateur comet hunters. This paper will describe the performance of this telescope system and plans for implementing this system at Lowell Observatory.

Introduction

The search for earth-crossing objects has become a very active field in the last several years. Earth-crossing objects consist of ~60% asteroids, ~20% long period comets and ~20% extinct comets (Shoemaker, 1995). There are many programs searching for earth-crossing asteroids. These telescopes have 1 ~ 2 meters of apertures but very small fields of view. To maximize the discovery rate for new asteroids these programs concentrate their searches on the region of sky near the ecliptic at opposition. However, this biased scanning strategy prevents discovery of higher inclination comets. Furthermore, the dynamics of Earth-cossing asteroids in the final weeks before their impacts with Earth show that they are bright (Mv < 16) and at very small solar elongation (Hills, 1995). In order to discover high inclination objects and objects at small solar elongation, a systematic survey of the entire available sky has to be performed each night. Such a survey is within the reach of automated, small to modest-sized telescopes with large fields of view.

In the past decade, experiments aimed at detecting near-Earth asteroids have been increasingly adding to the catalog of known comets. The Palomar Planet-Crossing Asteroid Survey (PCAS) and the Spacewatch program are described by Carusi et. al. (Carusi, 1995). PCAS, whose primary aim is the detection of asteroids in near-Earth space, has been in operation for nearly 20 years and uses the 0.46 m Palomar Schmidt telescope. The PCAS observations occur in dedicated campaigns spaced throughout the year. The technique involves taking pairs of photographs, covering 56 square degrees, of selected star fields, spaced 45 minutes apart, then examining them with a custom-designed stereomicroscope for evidence of objects that have moved against the stationary star background. The team can obtain between 50 and 60 images during a good night (representing 25 to 30 star fields.) The use of hyper sensitized Kodak 4415 film and 4 to 6 minute exposures achieves a limiting magnitude of V=17.5. The team also manages to do follow up observations on 30 to 50 objects for improved orbit determination. To maximize their sensitivity to asteroids, the team limits its observations to the 10% of the sky near the ecliptic, which is the most favorable part of the sky to scan for new asteroids. Due to the experience and dedication of the PCAS team the current annual sky coverage amounts to 40,000 to 50,000 square degrees per year. Current plans are to upgrade PCAS by adding a CCD (Charged Coupled Device) camera.

In 1991 a CCD based near-Earth object search became operative at the 0.91 m reflector at Kitt Peak. This was the Spacewatch program. The liquid-nitrogen cooled detector has 2048 x 2048 pixels and achieves a limiting magnitude of 20.5 with a 146.53 second integration time. This search is also limited to regions around the ecliptic in an effort to increase the likelihood of finding Earth-crossing asteroids with limited sky coverage.

More ambitious searches are under construction or consideration. The Spaceguard program plans to develop instrumentation to search the 6000 square degrees centered on the ecliptic at opposition down to magnitude 22, again concentrating on near-Earth asteroids. The Lowell Observatory Near-Earth Object Search (LONEOS) is currently instrumenting a 58 cm Schmidt with a four-chip CCD camera. LONEOS is designed to provide information that can be exported to Spaceguard.

Because of the limited inclination coverage, current and planned surveys are not optimized to find comets (Shoemaker, 1995). Furthermore, it is unlikely that the current and planned surveys will be quickly extended due to the expense of duplicating the large telescope systems in order to survey larger areas.

Optimal sensitivity to comets obviously requires a dedicated system that automatically surveys a large portion of the night sky, and can quickly and automatically recognize new objects. Automated target recognition requires CCD imagers whose digital output is directly compatible with computer processing. The high cost/area of CCDs demands that short focal length optics be used in order to cover a significant fraction of sky each night with a minimal number of CCDs. However, the short focal length requirement conflicts with attempts to increase the effective aperture.

Current and planned search experiments are resorting to very large format custom CCDs to obtain the largest field-of-view per image. This allows them to exploit meter class optics for maximum sensitivity to asteroids near the ecliptic. The resulting compromise emphasizes sensitivity over search area and revisit time.

An alternative approach which emphasizes search area and revisit time over sensitivity uses arrays of moderate aperture telescopes. We have found that modest cameras consisting of good-quality, commercially available telescopes, mounts, and CCDs can achieve sensitivities comparable to the PCAS program. Moreover the use of commercially available components significantly reduces the cost per camera. In this paper we show how a modest, fully-automatic, low-cost instrument can be built that can survey the entire available night sky on a weekly basis down to magnitude 17. We call the system FOCSE for Fast Optical Comet Search Experiment.

We have put together a collaboration from Lawrence Livermore National Laboratory (LLNL), the University of Michigan, and Lowell Observatory to implement and operate the FOCSE system. The collaborators from LLNL and the University of Michigan have previously collaborated on an automated telescope project (called GROCSE (Akerlof, 1993) for Gamma Ray Optical Counterpart Search Experiment) located at LLNL to search for optical counterparts of gamma ray bursts. The collaborators at Lowell bring their experience with the PCAS program to FOCSE.

Fast Optical Comet Search Experiment (FOCSE)

Figure 1 is a schematic of the proposed FOCSE system to be sited at Lowell Observatory. It consists of one or more sets of two 10 cm aperture f/3.3 telescopes mounted on a common mount protected by an automated clam shell. Each telescope is viewed by its own 2048 x 2048 pixel CCD with independent image acquisition and storage systems. A host computer operates the mount and sequences the imagery.

The combination of focal length and image format that we have chosen results in a 28.1 square degree field-of-view. The system requires 120 seconds per image including slewing time, integration time (100 sec), and transferring the image to disk. This results in 240 images centered on 120 star fields (two images per field) per camera per 8 hour night. A single camera, therefore, surveys 3370 square degrees per night. The four camera system proposed in this paper would survey 13,480 square degrees in 8 hours which is about one half of the total available night sky. Thus the system would revisit each star-field every two nights.

FOCSE Hardware

The FOCSE telescopes are manufactured by Tele Vue. The telescopes are a modified version of Tele Vue's commercial 10 cm aperture, f/5.4 Genesis telescopes. The modification consists of adding 3 new optical elements that shorten the focal length to f/3.3 and changing the spacing of the objective to better match the CCD spectral response. With a 2048 x 2048 CCD imaging device having 15 μm x 15 μm pixels the total field of view is 5.3° x 5.3° with each pixel subtending 9 arcsec. This semi-custom lens is commercially available at low cost and its optical quality is sufficiently high for our search, as proven in our prototype system (see the section of FOCSE Prototype System Performance).

The focal plane is a low noise Loral 2048 x 2048 pixel CCD with 15 μm x 15 μm pixels. Using a modified Loral CCD evaluation boards we measured the readout noise level to be < 50 electrons at room temperature. We are constructing new analog and digital camera boards which are much lighter, consume less power, have lower readout noise, and incorporate a thermal electric cooler to allow longer integration times.

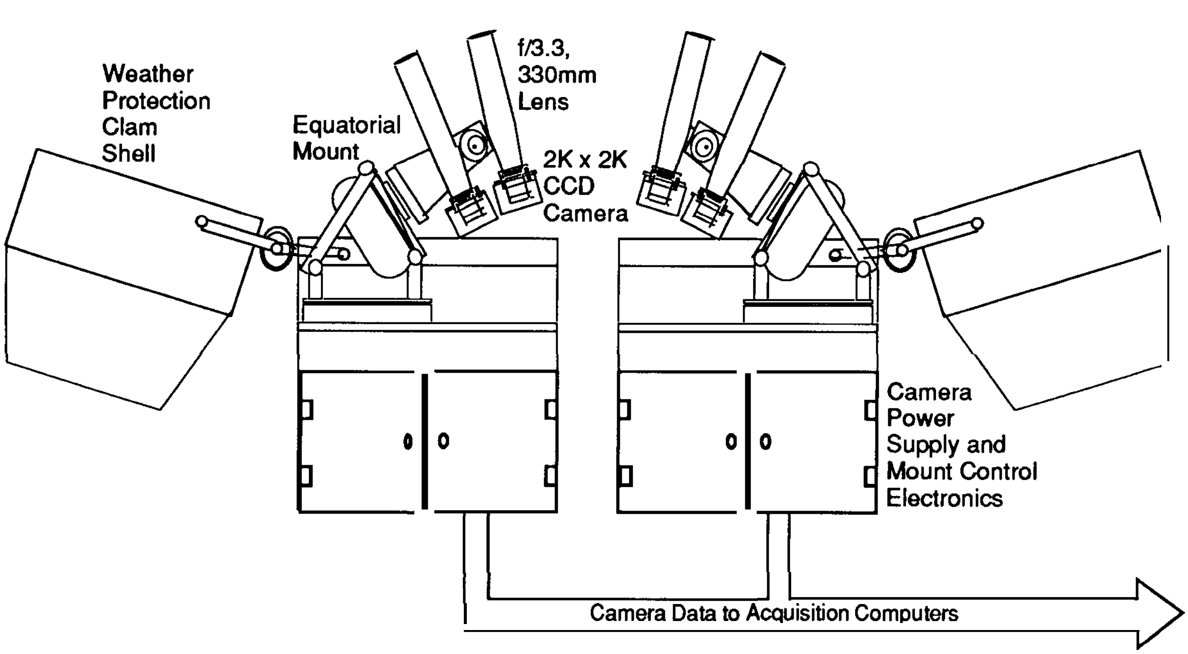


Figure 1. FOCSE Four Camera System and Weather Protection Clam Shell

Extensive laboratory calibration (Park, 1990) will be applied to produce the best processed images for extracting low signal to noise ratio objects. Pixel by pixel sensitivity and dark current calibration will remove the focal plane array (FPA) non-uniformity, fixed pattern noise, dark noise etc. at any integration time settings and any ambient temperature conditions. This pixel by pixel image calibration method gives more precise results than the traditional dark image subtraction and flat-field division at one given setting.

The robotic mount is manufactured by Epoch Instruments. It is of equatorial design and has separate motors for rapid slewing as well as tracking at earth rate. The mount can handle ~50 lbs of load and the tracking accuracy over 100 sec is better than 1 arcsec. The base size of this mount is only 16 " x 16" making it easy and affordable to construct a concrete base at the observatory site.

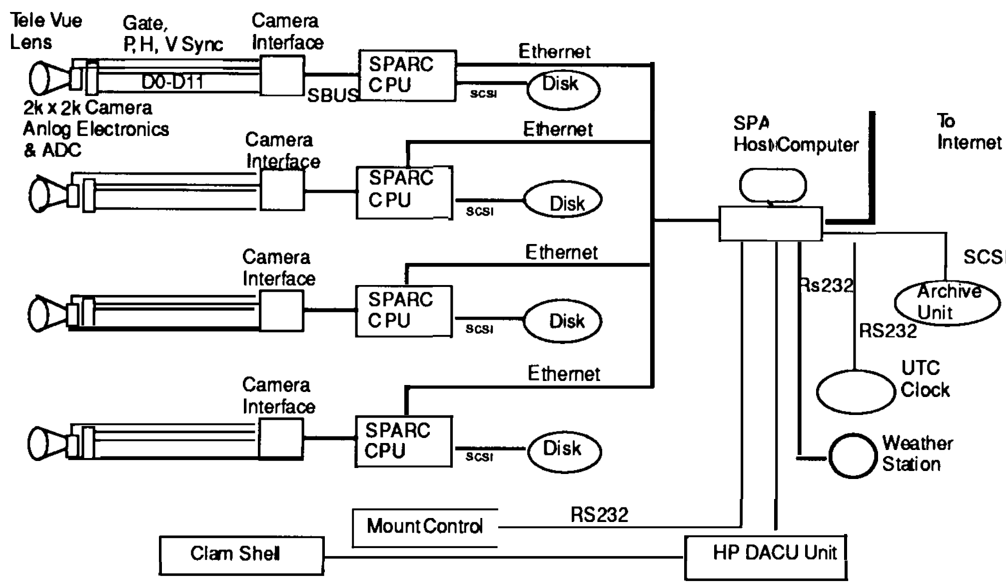
FOCSE Data Acquisition System

The data acquisition system is sketched in Figure 2. The camera digital and analog control electronics, including a 14 bit digitizer, are in the camera back plane. The digitized output, along with pixel, horizontal, and vertical sync signals, are serialized then transmitted to the SPARC image acquisition computer. Our custom frame buffer generates control signals for camera gain and integration time and transfers the images directly to the SPARC DRAM where it is accessed by the program then stored on the harddisk. The individual image acquisition CPUs are linked via ethernet to a main host computer (SPARC 10) which communicates over the internet, reads the UTC clock, controls the Epoch mount through an RS232 interface, archives the images taken at night, controls the clam shell (the telescope housing) and monitors the weather condition.

FOCSE Prototype System Performance

We assembled a prototype camera with an f/3.3 Tele Vue lens and a Loral 2048 x 2048 CCD read out with Loral's readout electronics. This "prototype" system was used to acquire imagery of M44 (Beehive) with 5 second integration time. Figure 3 shows a 0.64 degree portion extracted from the resulting images with identified star magnitudes marked on it. Mv > 14 stars are easily recognized in this image as expected from our radiometric model of the CCD and telescope.

It was not possible to integrate for 100 seconds (the nominal FOCSE integration time) with this prototype because of the design of the readout electronics and the tracking stability of the mount used for the test. Since the radiometric model correctly predicts the performance at 5 second integration time we used it to predict the performance at 100 seconds integration time. The model follows the method outlined in Rieke (Rieke, 1994), including estimates of all noise sources. The source was approximated as a blackbody of temperature 5800 K (reflected sunlight) with visual magnitude, zenith angle, and integration time as input variables. Bolometric correction and wavelength-dependent atmospheric transmission loss values listed in Allen (Allen, 1973) were used. Wavelength-independent instrument transmission losses of 2% per each of the five lens elements and an additional 2% loss due to particulates on the single, exposed objective were assumed. The wavelength-dependent quantum efficiency of the Loral CCD is based on our measured values, which conform closely to specifications. Atmospheric and optics transmission losses were multiplied by the sensor response to yield total atmosphere/instrument throughput efficiency. The input power from the source at the top of Earth's atmosphere was converted to number of photons, then multiplied by the atmosphere/instrument throughput efficiency to yield the total signal, in terms of photons/s, then integrated over all wavelengths to generate the total photon rate. The total signal was divided by the number of pixels for a point source, which was determined from the root-sum-square of the intrinsic spot size (< 1 arcsecond), the pixel size (9 arcseconds), and the seeing (in the model, seeing was fixed to 3 arcseconds). The following per pixel noise sources were included: shot noise, readout noise (measured at 50 e^- rms per pixel per frame), as measured dark current, out-of-wavelength band rejection, fixed pattern noise residual (set to 0.2% of signal), and sky background (set to mVsky = 22.0 for a dark site). The per pixel signal-to-noise ratio (SNR) was multiplied by the square root of the number of pixels subtended by a point source to yield total SNR at zenith, as plotted in Figure 4. The FOCSE instrument thus penetrates to better than 17th magnitude with SNR = 5 at zenith.



Fgure 2. FOCSE data acquisition system.

FOCSE Software

The FOCSE software is comprised of three main parts, the data acquisition and image processing software that runs on the image acquisition computers, the software running on the on-line host computer, and the long term analysis software that runs on computers at LLNL.

The data acquisition and image processing software runs on the image acquisition computers (SPARC 2s). When signaled by the host computer, the image acquisition software clears the CCD then starts the 100 second integration. During integration the software analyses the previous image. First the pixel-by-pixel calibration equation is applied to the image to eliminate the effects of dark current and pixel sensitivity non uniformity. The corrected image is passed to an image processing algorithm that identifies all star-like objects in the image. This algorithm was developed as part of LLNLs work on target recognition for ballistic missile defense. The algorithm computes the image mean and sample deviation then thresholds the image at the level of the mean plus 3 x the sample deviation. A connectivity algorithm is used to associate all pixels above the threshold into connected, star-like objects and compute the centroid, moments, and intensity of each object. The centroids are converted into RA and DEC. The information on all objects found in the image is stored in a table on the hard disk along with the image. If the image is a repeat of a previously imaged star-field, the program compares the absolute positions of the objects with those of the previous image searching for objects that have apparently moved. These objects are flagged and a notification is sent over the network to the host computer for further action such as scheduling follow-up observations that night.

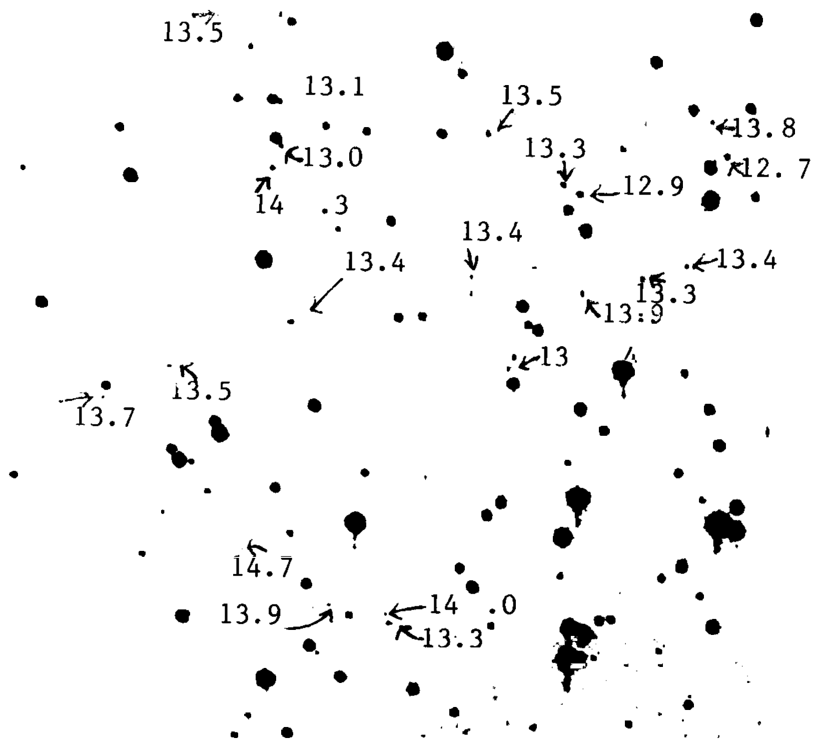


Figure 3. Highly magnified portions of imagery near M44 taken by prototype FOCSE camera utilizing the 330 mm focal length f/3.3 Tele Vue lens and Loral 2048 x 2048 pixel CCD imager. The field of view of the 256 x 256 pixel partial image reproduced here is 0.64 degrees. The magnitudes of stars identified in the Guide Star catalogue are marked.

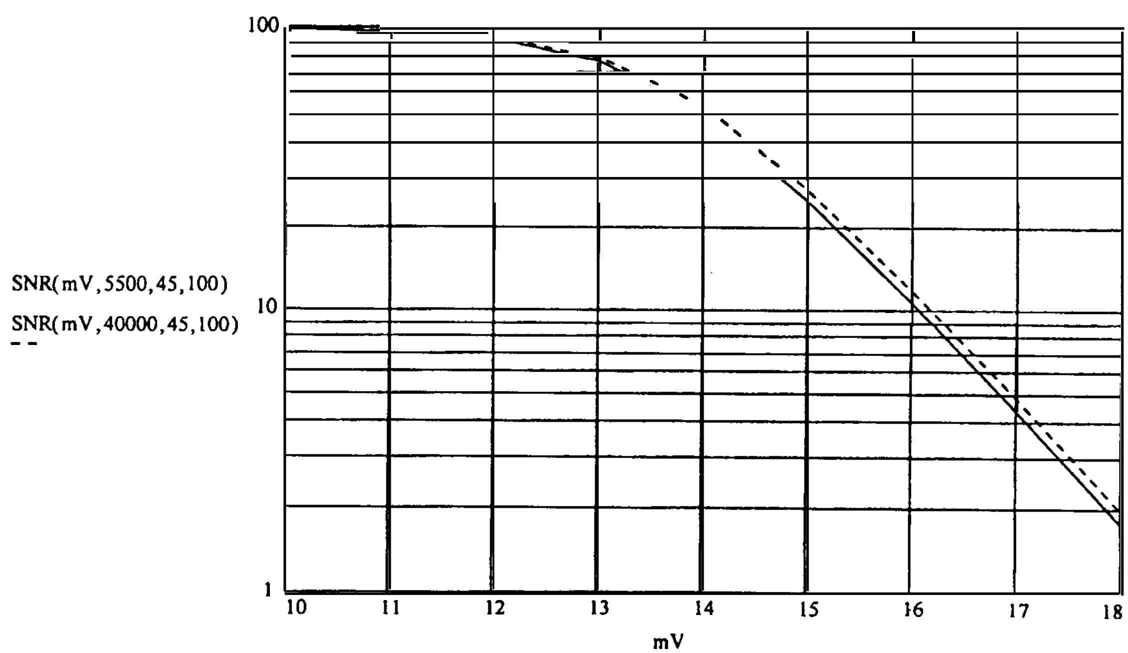


Figure 4. Signal-to-Noise Ratio Versus Visual Magnitude for 100 s Integration of 5,800 K Source.

When the 100 second integration time has passed, the image acquisition computer transfers the image to its memory for subsequent analysis.

The software running on the host computer (SPARC 10) initializes the system, checks the weather, and opens the clam-shell. It positions the Epoch mount for each star-field and signals the image acquisition computers to begin imagery or re-imagery. When the observations are complete for the night, the host computer closes the clam-shell and begins archiving the imagery and tables stored on the image acquisition disks. The tabular and image data are stored on a 17 GByte tape archival system.

The host also maintains a database of all objects found. The database is indexed by the RA and DEC of all objects found by the image acquisition computers. The host takes the entries from the image acquisition computer and associates them with previous entries according to their positions. New objects, or objects that have moved are flagged.

There is a lot of flexibility on how the host responds to moving objects identified by the data acquisition system. We envision that initially, frames containing moving objects will be examined by physicists for identification. Later, as we become more confidant in our system, the host may send coordinates of suspicious objects to other instruments over the internet. The host could also schedule additional observations of suspect star-fields automatically.

Long term analysis at LLNL involves looking through the host object table for interesting objects that have changed their characteristics.

Site

We have chosen the Anderson Mesa complex at Lowell Observatory as the site for the FOCSE system. The site has good seeing, and a large flat field that can accommodate observations down to within 20 degrees of the horizon. The site offers room for future construction of additional FOCSE telescopes to improve throughput.

Summary

We have shown that a dedicated 2x2 array of small telescopes can be used to search for long period comets in high inclination orbits. The systems makes maximum use of low cost commercially available components resulting in a system that can become operational on time scales of one year.

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